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EFFECTIVENESS OF A PROTOTYPE MICROCLIMATE COOLING SYSTEM FOR USE WITH CHEMICAL PROTECTIVE CLOTHING

NAVY CLOTHING AND TEXTILE RESEARCH FACILITY

NATICK, MASSACHUSETTS

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TECHNICAL REPORT NO. NCTRF 180

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION: Unclassified	1b RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release, distribution unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S): NCTRF Report No. 180	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION: Navy Clothing and Textile Research Facility; 6b. OFFICE SYMBOL (If applicable): 40	7a. NAME OF MONITORING ORGANIZATION: Naval Supply Systems Command
6c. ADDRESS (City, State, and ZIP Code): P.O. Box 59, Natick, MA 01760-0001	7b. ADDRESS (City, State, and ZIP Code): Commander, Naval Supply Systems Command, Washington, DC 20376-5000
8a. NAME OF FUNDING/SPONSORING ORGANIZATION: NAVSEA/NAVSUP; 8b. OFFICE SYMBOL (If applicable): 05R24/5512	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code): Commander, Naval Sea Systems Command, Washington, DC 20362; Commander, Naval Supply Systems Command, Washington, DC 20376-5000	10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO
62233N	TP2A	4	62-4-75

11. TITLE (Include Security Classification)
Effectiveness of a Prototype Microclimate Cooling System for use with Chemical Protective Clothing

12. PERSONAL AUTHOR(S)
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13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final	FROM Jul 89 TO May 90	90 December	21

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP
05	03	
23	04	

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
Microclimate Cooling Systems; Heat Stress; Chemical Protective Clothing; Physiological Testing; Thermal Manikin Testing

19. ABSTRACT (Continue on reverse if necessary and identify by block number) The Navy Clothing and Textile Research Facility conducted laboratory evaluations of a prototype, portable microclimate cooling system (MCS) designed for use with chemical protective clothing. The MCS circulates chilled liquid through a torso vest. A backpack unit contains an ice pack; a pump and motor assembly and a rechargeable battery are mounted on a chest or waist strap. Total weight of the MCS is 9.3 kg (20.4 lbs). To examine the effectiveness of the system in reducing heat strain, seven male test subjects participated in a laboratory heat stress evaluation. To determine the cooling power and efficiency of the MCS, thermal manikin testing was conducted. (U)

During the heat stress evaluation, the subjects attempted 120-min heat exposures in a 35°C (95°F), 60% humidity environment while exercising at a time-weighted rate of approximately 300W. They were tested four times: with and without the MCS while they wore a semi-permeable and an impermeable chemical protective ensemble. Exposure time in all cases was 120 min, except when the impermeable ensemble was worn without the MCS (mean tolerance time = 96 min). Use of the MCS significantly reduced rectal temperature by an average of 0.5°C (cont'd)

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21 ABSTRACT SECURITY CLASSIFICATION: Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL: John A. Mylotte	22b TELEPHONE (Include Area Code): 508/651-4680; 22c. OFFICE SYMBOL: OOP

BLOCK 19. ABSTRACT

(0.9°F) after 120 min with the semi-impermeable ensemble and by 1.3°C (2.3°F) after 100 min with the impermeable ensemble. Mean weighted skin temperature was significantly lower by an average of 3.3°C (5.9°F) when the MCS was used. Use of the MCS significantly reduced heart rate by 30 and 42 b/min with the semi-impermeable and impermeable ensembles, respectively. Sweating rate was also significantly reduced, by an average of 37%. (U)

The thermal manikin tests were conducted in a 35°C (95°F), 60% relative humidity environment with the manikin surface temperature maintained at 35°C (95°F) and a fully wetted skin. When the semi-permeable chemical ensemble was worn, the MCS removed 326 watt-hours of energy at an average rate of 122 watts. With the impermeable ensemble, the MCS removed 308 watt-hours of energy at a rate of 151 watts. The calculated theoretical cooling power of the MCS was 538 watt-hours. The efficiency of the systems, therefore, was 61 and 58% with the semi-permeable and impermeable ensembles, respectively. (U)

During the total of 62 hours the MCS was used during the heat stress evaluation, a number of durability and reliability problems occurred. These included ice pack leaks, crimped hoses, accidental disconnects, frozen pumps, and air in the cooling tubes. Considering that this was the initial prototype of a newly-developed MCS, however, the system performed fairly well. Further development and/or modifications to the existing system would be required to make it suitable for Navy use. (U)

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Part I: HUMAN EVALUATION

INTRODUCTION

For several years, the Navy Clothing and Textile Research Facility (NCTRF) has evaluated commercially-available, microclimate cooling systems (MCS) for potential shipboard use (1-5). One system - the SteeleVest (Steele Inc., Kingston, WA) - has been shown to be effective in reducing heat strain (4-7) and has recently been approved for general shipboard utility use. The SteeleVest consists of an externally-insulated, cotton canvas vest which holds frozen gel packs against the torso. It has been shown to be as effective as the other circulating liquid or air-cooled systems that were tested. Because the SteeleVest is a "passive" cooling system, however, it has several advantages over the other types of MCS. It has no mechanical parts, does not require batteries or an air source, is relatively lightweight, inexpensive, has a low profile and is easy to use. Research at NCTRF is continuing to evaluate the effectiveness of this particular system when used in different environments and at various work rates, and to develop guidelines for maximum safe exposure times when the MCS is used.

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(1) Janik, C. R., B. A. Avellini, and N. A. Pimental. Microclimate cooling systems: a shipboard evaluation of commercial models. Natick, MA: Navy Clothing and Textile Research Facility, 1987; Technical Report No. 163.

(2) Giblo, J., and B. A. Avellini. Outfitting Navy ships with microclimate cooling systems: an engineering evaluation to determine the initial costs. Natick, MA: Navy Clothing and Textile Research Facility, 1989; Technical Report No. 174.

(3) Pimental, N. A., B. A. Avellini, and C. R. Janik. Microclimate cooling systems: a laboratory evaluation of two commercial systems. Natick, MA: Navy Clothing and Textile Research Facility, 1988; Technical Report No. 164.

(4) Pimental, N. A., and B. A. Avellini. Effectiveness of three portable cooling systems in reducing heat stress. Natick, MA: Navy Clothing and Textile Research Facility, 1989; Technical Report No. 176.

(5) Pimental, N. A., and B. A. Avellini. Effectiveness of a selected microclimate cooling system in increasing tolerance time to work in the heat. Natick, MA: Navy Clothing and Textile Research Facility, 1990; Technical Report No. NCTRF 181.

(6) Glenn, S. P., P. A. Jensen, J. B. Hudnall, W. D. Eley, and C. S. Clark. An evaluation of three cooling systems used in conjunction with the U.S. Coast Guard Chemical Response Suit. American Industrial Hygiene Conference, St. Louis, MO, May 1989.

(7) Banta, G. R. Helicopter in-flight heat strain and effect of passive microclimate cooling. Aviat. Space Environ. Med. 61: 467, 1990.

When an MCS is used with chemical protective clothing, there are several unique requirements for the system. Although the vest should be worn close to the torso, the coolant (e.g., ice pack) and the power source (e.g., battery) must be located on the outside of the garment to facilitate resupply. The connections between the vest and the outside components of the MCS must not compromise the chemical protection of the garment. The cooling system must be able to be chemically decontaminated. The SteeleVest does not meet the first requirement of having the coolant located on the outside of the garment. Other existing MCS do not meet all of these specialized requirements and/or are not reliable or easy enough to use. Therefore, NCTRF contracted an outside manufacturer to design and develop a prototype system for use with the Navy chemical protective ensemble. The contract for the prototype MCS specified that the system should be a portable, liquid cooling system with a replaceable ice pack and a rechargeable power source (battery). It also specified that the system should provide an average body heat removal rate of 300 watts with a total capacity of 600 watt-hours, and that the battery should operate for 2 hours before recharging was needed. The total weight of the system was not to exceed 9.1 kg (20 lbs).

Currently, the Navy has two configurations of chemical protective clothing: the Mark III and the Mark III worn with the Navy Wet Weather ensemble. The Mark III is a semi-permeable, two-piece garment (trousers and smock with attached hood), with a clo value of 2.0 and an i_m value of 0.42 measured at 0.3 m/s wind velocity. Under conditions of potential liquid chemical contamination or exposure to ocean spray, the Navy Wet Weather ensemble may be worn over the Mark III, thereby making the clothing ensemble impermeable. The Wet Weather ensemble consists of bib front overalls and a parka constructed of chloroprene-coated nylon twill. The clo and i_m values of the Wet Weather ensemble worn over the utility uniform and Mark III are 2.4 and 0.24, respectively.

The purpose of the present evaluation was to evaluate the effectiveness of the prototype, circulating liquid MCS in reducing physiological strain of subjects working in the heat while wearing the Navy chemical protective ensembles.

METHODS

Description of Cooling System. The prototype MCS was made by ILC Dover (Frederica, DE). The system includes a cotton-lined, mesh vest threaded with plastic tubing, a backpack unit containing an ice pack, and a pump and motor assembly and rechargeable 24-volt battery which are mounted on the chest or waist straps. The ice pack contains 4.6 kg (10.1 lbs) of water and detaches from the backpack for freezing. The circulating liquid (30% ethylene glycol) travels through coiled tubing inside the ice pack and into the vest. The total weight of the system is 9.3 kg (20.4 lbs). The dimensions of the ice pack are 46 (h) x 33 (w) x 9 (d) cm (18 x 13 x 3.5 in). The dimensions of the pump and motor assembly are 11 x 10 x 5 cm (4.5 x 3.75 x 2 in). The dimensions of the battery are 6 x 13 x 5 cm (2.25 x 5.25 x 2 in).

Test Design. Seven male subjects participated in the evaluation (average age, 20 yr; height, 178 cm; weight, 74.5 kg). They were initially heat acclimated for 2 weeks by daily, 2-hour heat exposures in a 35°C (95°F), 75% humidity environment. Each subject then participated in four tests in random order:

1. Mark III (MKIII Control)
2. Mark III plus microclimate cooling system (MKIII with MCS)
3. Mark III with Wet Weather ensemble (MKIII+WW Control)
4. Mark III with Wet Weather ensemble plus cooling system (MKIII+WW with MCS)

In all tests, subjects also wore the Navy utility uniform (T-shirt, long-sleeved chambray shirt and denim trousers), butyl gloves with cotton liners, socks, sneakers, butyl footwear covers and the Navy Mark V gas mask (without filters). When the cooling system was used, the vest was worn over the T-shirt and chambray shirt. The pump and motor assembly and the battery were mounted on the waist strap. Testing was conducted in a controlled climatic chamber. Environmental conditions were 35°C (95°F) dry bulb temperature, 60% relative humidity, with 0.9 m/s (2 mph) wind velocity. Each heat exposure was 2 hours, or until one of the termination points described below was reached. During the heat exposures, subjects alternately walked on a level treadmill at 1.1 m/s (2.5 mph) for 20 minutes and sat for 10 minutes. Including the added cost of wearing the chemical ensemble and carrying the 20-lb MCS, this resulted in a time-weighted metabolic rate of approximately 300 watts. This rate was selected in order to assess whether the MCS could meet the design requirement of removing body heat at a rate of 300 watts. Any subject was removed early from the heat exposure if his rectal temperature exceeded 39.5°C (103.1°F) or rose at a rate greater than 1.8°C (3.2°F) in 5 minutes, if his heart rate exceeded 180 b/min for 5 continuous minutes during exercise or 160 b/min for 5 minutes during rest, or if he was unable to continue walking unassisted. To prevent significant dehydration, subjects were encouraged to drink water during the heat exposures and consumption was monitored.

Measurements. During the heat exposures, rectal temperature was measured using a thermistor inserted approximately 10 cm (4 inches) beyond the anal sphincter. Skin temperatures were measured using thermocouples on the chest (shielded to prevent direct contact with the cooling vest), forearm and calf. Mean weighted skin temperature was calculated according to the formula of Burton (8). Rectal and skin temperatures were plotted and printed every 2 minutes on a computer-controlled data acquisition system. The electrocardiogram was obtained from chest electrodes (CM5 placement) and displayed on an oscilloscope and cardiotachometer unit. Total body sweating rate was calculated from pre- and post-test nude body weights, adjusted for water consumption.

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(8) Burton, A. C. Human calorimetry II. The average temperature of the tissues of the body. Journal of Nutrition 9: 261-280, 1935.

The cooling system's ice pack was frozen to -15°C (5°F). During testing, thermocouples were placed in the circulating fluid at four points: immediately exiting the ice pack, entering the vest, exiting the vest, and reentering the ice pack. Because the system was designed to operate for 2 hours without resupply, the ice packs were not changed during the 2-hour tests. Battery voltage was monitored at regular intervals with a digital multimeter. Failures of the system were corrected if possible as they occurred and these were recorded.

Statistical Analysis. To compare the MCS to Control data, separate repeated measures analyses of variance were performed on the MKIII and the MKIII+WW data. The rectal temperature, skin temperature and heart rate data were analyzed using two-way (MCS/Control vs. time) analyses of variance. The sweating rate data were analyzed using one-way (MCS/Control) analyses of variance. The MKIII data were analyzed at 20-minute intervals for the full 120 minutes. Due to subject attrition, the MKIII+WW data were analyzed up to 100 minutes only. Missing values were estimated using least squares. Tukey's test was used to locate significant differences. Significance was accepted at the 0.05 level.

RESULTS

Exposure Time. When the MKIII was worn both with and without the MCS, all subjects were able to complete the 120-minute heat exposures. When the MKIII+WW was worn with the MCS, exposure time was also 120 minutes. During the MKIII+WW Control test, only one of the seven subjects was able to complete the exposure. Exposure times for the remaining subjects ranged from 78-110 minutes. Of the early terminations, one was due to reaching the pre-determined heart rate limit (>180 b/min for 5 minutes). The others were because of inability to continue walking unassisted due to nausea, faintness, weakness, and/or hyperventilation. In each of those cases, final heart rate was ≥172 b/min or rectal temperature was ≥39.0°C (102.2°F).

Rectal Temperature. Figure 1 illustrates rectal temperature responses with and without the MCS when the MKIII and MKIII+WW were worn. When the MKIII was worn, there were no significant differences between Control and MCS in rectal temperature responses for the first 80 minutes of exposure ($p>0.05$). At 100 and 120 minutes, however, rectal temperature with the MCS was significantly lower than Control ($p<0.05$). Final rectal temperature at 120 minutes averaged 37.5°C (99.5°F) and 38.0°C (100.4°F) for MCS and Control, respectively. When the MKIII+WW was worn, there were no significant differences in the rectal temperature response for the first 40 minutes of heat exposure. From 60 minutes on, temperature with the MCS was lower than Control ($p<0.05$). At 100 minutes, rectal temperature averaged 37.7°C (99.9°F) and 39.0°C (102.2°F) for MCS and Control, respectively.

Mean Weighted Skin Temperature. Mean weighted skin temperature data are presented in Figure 2. When the MKIII was worn, skin temperature was significantly lower with the MCS from 20 minutes on, by an average of 3.3^{o}C (5.9^{o}F). With the MKIII+WW, skin temperature was also significantly lower with the MCS from 20 minutes on, by an average of 3.4^{o}C (6.1^{o}F). Skin temperature with the MKIII at 120 minutes averaged 32.9^{o}C (91.2^{o}F) and 36.4^{o}C (97.5^{o}F) for MCS and Control, respectively. With the MKIII+WW, skin temperature at 100 minutes averaged 35.2^{o}C (95.4^{o}F) and 38.7^{o}C (101.7^{o}F) for MCS and Control, respectively.

Heart Rate. Figure 3 illustrates heart rate responses during the four test conditions. The peaks represent average heart rates at the end of each 20-minute exercise bout; the lower points represent averages at the end of each 10-minute rest period. When the MKIII was worn, there were no significant differences between MCS and Control for the first 60 minutes. From 70 minutes on, however, heart rate was lower during MCS tests than Control tests ($p<0.05$). Heart rate during the final rest period averaged 80 and 107 b/min for MCS and Control, respectively. During the final exercise bout, heart rate averaged 110 and 141 b/min for MCS and Control, respectively. With the MKIII+WW, heart rate was significantly lower for MCS compared to Control from 40 minutes on. Heart rate during the final rest period averaged 93 and 142 b/min for MCS and Control, respectively. At the end of the third exercise bout (90 min), heart rate averaged 125 and 167 b/min for MCS and Control, respectively.

Sweating Rate. Total body sweating rates are presented in Figure 4. When the MCS was used with either clothing ensemble, sweating rates were significantly lower than Control. With the MKIII, sweating rate averaged 340 and 554 g/m^2/h for MCS and Control, respectively. With the MKIII+WW, sweating rate averaged 527 and 794 g/m^2/h for MCS and Control, respectively.

Reliability of Cooling System. Two complete cooling systems plus one extra ice pack, two extra batteries and two battery chargers were provided by the contractor. Only one system was used at a time during the heat stress testing, and the other system was used as a backup. The systems were used for approximately 20 hours prior to testing (benchtop testing), 28 hours during testing, and 14 hours between tests (maintenance and troubleshooting), for a total of 62 operating hours. During this operating time, several durability and reliability problems occurred. All three ice packs developed leaks along the seam. There were numerous cases of crimped hoses and two cases of disconnected hoses. These occurred at the hose connection to the base of the ice pack while the subjects were seated. On three occasions, the motors became inoperable and required repair. In each case, the problem was due to particulate buildup inside the motor from wearing of the motor brushes. After every test, it was noticed that excessive air had been introduced in the circulating fluid lines. This air had to be purged from the ice pack and vest after each test. There was one case of a broken connector for the waist strap. An average of 1 hour of support work was required for every 2 hours of actual use.

Coolant Life. Figure 5 illustrates the temperature of the circulating fluid exiting the ice pack when the MCS was used with the MKIII and with the MKIII+WW. The graph is an average of those tests during which operational difficulties of the MCS did not occur. Initial coolant temperature averaged -10°C (14°F), rapidly rose to near freezing and remained fairly stable as the ice pack melted until about 80 minutes, and then began to rise due to all of the ice being melted. There was no significant difference in coolant temperature with the MKIII and MKIII+WW. Figure 6 shows a typical graph of what the coolant temperature response when the MCS experienced a problem. At about 90 minutes, a hose became crimped and coolant flow stopped. This caused the temperature of the circulating fluid to rise rapidly for several minutes until the crimp was relieved and circulation restored.

DISCUSSION AND CONCLUSIONS

Effectiveness of System in Reducing Heat Strain. Use of the prototype MCS significantly reduced thermal strain, as evidenced by lower rectal and skin temperatures, heart rates and sweating rates. The reduction in heat strain was more pronounced when the MKIII+WW was worn than when the MKIII alone was worn. This was probably due to the increased thermal strain with the MKIII+WW as a result of the reduced ability of the subjects to dissipate heat through the evaporation of sweat. When the Wet Weather ensemble is worn over the MKIII, the i_m/clo ratio (0.10) is approximately one-half that of when the MKIII alone is worn (0.21), resulting in the lowered evaporative heat loss. During the Control test, only one of the seven subjects wearing the MKIII+WW was able to complete 2 hours of light exercise in the 35°C (95°F) environment. Use of the MCS enabled all subjects to complete the 2-hour heat exposure. The reduction in the core temperature when the MCS was used is illustrated in Figure 1. After less than 2 hours of heat exposure, rectal temperature during the control test averaged 39.0°C (102.2°F). This core temperature represents one of the physiological "end-points" used by the Navy to define maximal safe exposure time for shipboard personnel (9). When the prototype MCS was used, rectal temperature under the same conditions averaged 37.7°C (99.9°F). Use of the MCS also resulted in a significant reduction in cardiovascular strain. After less than 2 hours of heat exposure, heart rate was lower by an average of 49 and 42 b/min during rest and light exercise, respectively.

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(9) Dasler, A. R. Heat stress, work function and physiological heat exposure limits in man. In: Thermal Analysis-Human Comfort-Indoor Environments, National Bureau of Standards, Washington, D.C., 1977.

When the MKIII alone was worn, the difference between the Control and MCS tests was less dramatic. This may have been because even without the MCS, the level of thermal strain was only moderate. Rectal temperature after 2 hours of heat exposure during the Control test had only risen to 38.0°C (100.4°F). This core temperature, which corresponds to the NIOSH Permissible Exposure Limit for an 8-hour period (10), is a level normally associated with only slight decrements in mental performance. If the test conditions had been more severe, the effect of the MCS may have been more pronounced.

When either the semi-permeable or impermeable clothing ensemble was worn, use of the cooling system reduced sweating rates and subsequently, drinking water requirements, by 34-39%. This is of particular concern when chemical protective clothing is worn and hypohydration may become a problem because of drinking procedures with the facemask.

A number of other studies have examined the effectiveness of MCS in reducing heat strain when chemical protective clothing is worn. Those MCS did not necessarily meet all of the design criteria specified for the prototype MCS used in the present evaluation. Several studies examined various liquid-cooled and gas-cooled MCS when the Army chemical protective ensemble was worn. The Army ensemble is heavier and less permeable than the MKIII. Because of the difference in clothing, environments and metabolic rates, however, the results of those studies are difficult to compare to the present evaluation of the prototype MCS. One previous study at NCTRF evaluated the effectiveness of an air-cooled MCS on subjects wearing the MKIII in the same environment as the present evaluation but exercising at a higher metabolic rate (11). Despite the more severe test condition, use of the air-cooled MCS resulted in similar rectal temperature and lower skin temperature, heart rate and sweating rate than the prototype MCS.

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(10) Dukes-Dobos, F. N., and A. Henschel. Development of permissible heat exposure limits for occupational work. Am. Soc. Heat. Refrig. Air Cond. Eng. J. 15: 57-62, 1973.

(11) Pimental, N.A., C.R. Janik, and B.A. Avellini. Effectiveness of various microclimate cooling systems in reducing heat stress. Natick, MA: Navy Clothing and Textile Research Facility; In-house Report, 1987.

Reliability of System. The reliability, durability and required maintenance of a MCS is an important concern. The prototype MCS experienced a number of problems, some of which may be easily solved and others which were more troublesome. One of the ice packs leaked the first time it was filled with water. This and the two other leaks which developed later were repaired with silicon adhesive. The problems with the crimped and disconnected hoses could probably be eliminated by redesigning the system so that the hose connections are relocated. To avoid the problem with the broken strap connector, the plastic strap must be made stronger at this point. The problem with the motors is particularly troublesome. There were three failures in only 62 hours of operation. All three failures were traced to the buildup of particulate matter in the motor. The particulates were probably from the electrical contacts which may be wearing down as the motor rotates. A more powerful motor, or one that is a different design may solve this problem, although this may increase the weight of the system. The problem of air entry into the system reduces the cooling efficiency of the MCS and, in a chemically contaminated environment, may also provide a means of entry for toxic substances beneath the chemical protective overgarment. It is theorized that the air was introduced into the system through the vent and/or fill valves used to remove air and add cooling fluid prior to use. Use of these valves for the refill procedure proved to be a slow and imperfect method. Attaching the refill container directly between the pump and vest or between the pump and ice pack proved to be more rapid and effective. Therefore, eliminating the vent/fill valves altogether may solve, or at least diminish, the air problem.

Conclusions. The prototype MCS was effective in alleviating heat strain and enabled subjects wearing chemical protective clothing to complete a 2-hour heat exposure in a 35°C (95°F) environment. As currently designed, however, the system is not operationally reliable or rugged enough for near-term Navy use. Further development and/or modifications to the prototype system are required.

EFFECTIVENESS OF A PROTOTYPE MICROCLIMATE COOLING SYSTEM FOR USE WITH CHEMICAL PROTECTIVE CLOTHING

Part II: THERMAL MANIKIN EVALUATION

INTRODUCTION

The purpose of this evaluation was to assess the theoretical and actual cooling capability of the prototype MCS. The two most common methods for determining the heat absorbed by an MCS are: 1) calculations of heat absorbed by the vest as determined by fluid flow rate and inlet and outlet fluid temperatures, and 2) measurements of power supplied to a Thermal Manikin (TM) in the control versus cooled condition. Calculations of heat absorption based on fluid flow rate and temperature are considered inaccurate because this method fails to distinguish between heat absorbed from the individual (or test heat source) and heat absorbed from the environment. However, the use of a TM permits direct measurement of the heat absorbed by the vest from the heat source (i.e. TM). Therefore, we utilized the TM method for determining the heat absorption capability of the MCS.

Five parameters were identified as being useful wher. evaluating the cooling capability of a liquid MCS. First, the theoretical cooling capacity is important since it identifies the maximum cooling potential of the MCS. Actual cooling capacity is important since it describes the total amount of actual cooling provided to the user by the current system. Third, the efficiency of the system provides a representation of how close the actual capacity comes to its theoretical capacity, and thereby indicates how much room there is for improvement in the design of the system. The last two parameters, ice reserve life and average cooling rate, indicate how long the system will last, and how quickly it removes heat. These parameters are valuable since they indicate in a practical way the cooling that a user of the system should expect.

METHODS

Test Design. The TM is a ten-zone, heated aluminum manikin with the dimensions of a 50th percentile male. The TM is fitted with a sweating skin which is made of cotton cloth onto which is affixed narrow diameter perforated tubing. Water is pumped through the perforations of the tubing to keep the cotton skin fully wetted, thus simulating the heat transfer and evaporative effects of sweating.

In all tests, the TM wore the MCS in either the Mark III (MKIII) or Mark III + Wet Weather Ensemble (MKIII+WW). A description of the ensembles is included in Part I. Two tests were completed with each ensemble. The vest and backpack were worn during the control phase (no cooling, as described below) in order to simplify the cooling power calculations (i.e., by eliminating the change in clothing insulation that would result if the cooling system was not worn during control, but was worn during MCS testing). This follows the method of earlier studies (12,13). The environmental conditions during the tests were identical to those of the physiological evaluation, i.e., 35°C (95°F) dry bulb, 60% relative humidity, and 0.9 m/s (2 mph) wind speed.

Each test consisted of two phases, a Control (no cooling) phase followed by a Cooling phase. During the Control phase, the TM was allowed to reach thermal equilibrium with the cooling system turned off, and no ice reserve in the backpack. Once thermal equilibrium was reached, the amount of power required by the TM to maintain surface temperature was noted. At this point, an ice reserve, frozen at approximately -15°C (5°F, the same temperature as in the physiological study) was placed into the backpack, the hoses were connected, and the cooling system was turned on. This began the Cooling phase of the test. The power required by the TM was recorded at one minute intervals during the Cooling phase. The difference between the power consumed during the Control phase and the power consumed during the Cooling phase indicates the cooling power of the MCS. During the Cooling phase of the test, the temperature of the fluid entering the vest was monitored until it reached 18°C (65°F), at which point the test was ended.

The 18°C (65°F) limit was chosen since this temperature represents a 50% reduction in cooling rate. It is well known that the rate of heat transfer is proportional to the temperature difference between the hot and cold sides of the heat exchange. In a 100% efficient MCS on a 35°C TM, this temperature difference would be 35°C while the ice was melting at 0°C. Once the ice was completely melted, however, the temperature of the circulating fluid entering the vest would begin to rise, resulting in a decrease in the temperature difference between the TM and the circulating fluid. This decrease in temperature difference would be accompanied by a proportional decrease in cooling rate. Arbitrarily, we selected a 50% decrease in cooling rate as the limit of effective cooling. This translates into a circulating fluid temperature entering the vest of approximately 18°C.

The ice reserve was not changed during a test; however, the battery pack was changed as needed to keep the system operational. Conducting the test in this way permitted determination of the limits of the ice reserve separately from limits of the battery pack. A separate study of the battery pack has been conducted and is being reported elsewhere.

(12) Fonseca, G., Effectiveness of ice (water) packets vests in reducing heat stress. Natick, MA: USARIEM, 1982; Technical Report No. T3/82.

(13) Fonseca, G., Effectiveness of two portable liquid-cooled undergarments in reducing heat stress. Natick, MA: USARIEM, 1983; Technical Report No. T3/83.

Measurements and Calculations. A computerized data acquisition system was used to collect circulating fluid temperature data from the MCS. Thermocouples were placed in the circulating lines of the MCS at four points: entering and exiting the ice pack, and entering and exiting the vest itself.

The required calculations included theoretical cooling capacity, actual cooling capacity, efficiency, and average cooling rate. The theoretical cooling capacity of the MCS is based on the amount of ice or water in the ice reserve and the allowable temperature rise. There are two equations which govern the theoretical cooling capacity of the MCS. The first equation describes the cooling associated with heat absorption by the ice (before melting) as it rises from its initial temperature to $0^{o}C$ ($32^{o}F$). The first equation also describes the cooling associated with the heat absorption by the water (after the ice has melted) as it rises from $0^{o}C$ ($32^{o}F$) to its final temperature. The first equation is as follows:

$$Q = MC(T_f - T_i) \qquad \text{equation (1)}$$

where:

Q = heat absorbed
M = mass of ice or water in the ice pack
C = heat capacity of ice or water
T_f = final temperature
T_i = initial temperature.

Any consistent system of units may be used in this equation.

The second equation describes the heat absorption of the ice as it melts at $0^{o}C$ ($32^{o}F$). The second equation is as follows:

$$Q = MH \qquad \text{equation (2)}$$

where:

H = latent heat of fusion of ice
and other variables are defined above.

As in the first equation, any consistent system of units may be used.

The theoretical cooling capacity was calculated by using the first equation to calculate the heat absorbed by the ice as it rose to its melting point ($0^{o}C$, $32^{o}F$) followed by use of the second equation to calculate the heat absorbed by the ice as it melted. Next, the first equation was used again to calculate the heat absorbed by the water as its temperature rose above $0^{o}C$ ($32^{o}F$). Finally, the three heat absorption values were summed to determine the theoretical cooling capacity of the MCS.

Before the theoretical cooling capacity could be calculated it was first necessary to establish initial (ice) and final (water) temperatures in the ice pack. In the TM and physiological tests, the ice packs were frozen to approximately -15°C (5°F). However, by the time the ice packs were transferred from the freezer to the backpack, the hoses connected, and the system started, the temperature of the ice in the backpack had risen to approximately -10°C (14°F). Therefore, it seemed reasonable to select -10°C (14°F) as the starting temperature for the theoretical cooling capacity calculation. As described earlier, the TM tests were discontinued when the temperature of the fluid entering the vest reached 18°C (65°F), therefore this temperature was selected as the final temperature for the theoretical cooling capacity calculation. The time required to reach this end point was termed the ice reserve life of the MCS.

The actual cooling capacity was calculated from the power input to the TM. The power input was recorded every 60 seconds. The control (no cooling) power input was subtracted from each of the 60-second power input readings taken during the cooling phase. This yielded the rate of heat absorption by the vest from the TM for each 60-second interval. To convert the rate of heat absorbed during each 60-second interval to the quantity of heat absorbed during each interval, the rates were multiplied by time. These results were then summed for the full length of the test to derive the actual cooling capacity of the MCS.

Efficiency was calculated by dividing the actual cooling capacity by the theoretical cooling capacity, and multiplying by 100 to obtain percent.

Average cooling rate was calculated by dividing the actual cooling capacity by the ice reserve life of the system.

RESULTS

Results of the TM tests are shown in Table 1. Based on an initial ice temperature of -10°C (14°F) and a final water temperature of 18°C (65°F), the theoretical cooling capacity of the ice reserve was 538 watt-hours. Most of the cooling (78%) was provided by the heat of fusion of the ice as it melted (equation (2)).

The average actual cooling capacity of the MCS when worn under the MKIII was 326 watt-hours. When worn under the MKIII+WW, the average actual cooling capacity was 308 watt-hours. This represented MCS efficiencies of 61 and 58% respectively.

The average ice reserve life of the MCS when worn under the MKIII was 163 minutes (2.7 hours). When the WW was added, the average ice reserve life was 123 minutes (2.0 hours). The average cooling rates of the MCS worn with the MKIII alone and worn with the MKIII+WW were 122 and 151 watts, respectively.

TABLE 1: THERMAL MANIKIN EVALUATION RESULTS

Theoretical cooling capacity: 538 watt-hours.

Ensemble	Actual Cooling Capacity (watt-hrs)	Efficiency (%)	Ice Reserve Life (min)	Average Cooling Rate (watts)
MKIII Mean ± S.D.	326±35	61±6	163±32	122±11
MKIII+WW Mean ± S.D.	308±12	58±2	123±4	151±2

DISCUSSION AND CONCLUSIONS

The theoretical cooling capacity of 538 watt-hours is fairly close to the Navy goal of 600 watt-hours. By way of comparison, the LSSI Cool Head liquid MCS and the ILC Dover Cool Vest have theoretical cooling capacities of 250 watt-hours (5.2 pounds of a frozen glycol/water mixture) and 323 watt-hours (6.0 pounds of ice) based on the same temperature rise from -10 to 18°C (14 to 65°F). (Note: The differences between the cooling capacity of the prototype MCS and the two commercial MCS is due to the greater amount of ice in the prototype than in the other systems; and in the case of the LSSI system, is also due to the lower heat of fusion and lower heat capacity of the glycol/water mixture versus pure ice.) For the prototype MCS, calculations show that if the ice in the ice pack is increased from 4.6 to 5.0 kg (10.1 to 11.1 pounds), then the desired cooling power would be achieved. This additional weight in ice, however, will increase the total weight of the system from 9.3 to 9.7 kg (20.4 to 21.4 pounds), 0.6 kg (1.4 pounds) greater than the desired 9.1 kg (20.0 pounds) limit. The system as delivered is already 0.2 kg (0.4 pounds) greater than desired.

The actual cooling capacities of 326 and 308 watt-hours translate into efficiencies of 61 and 58% respectively. It is theorized that the actual cooling capacity and efficiency of the MCS can be increased by reducing heat absorption from the environment. During the TM tests, the temperature of the circulating fluid rose by 5 to 10°C (9 to 18°F) as it flowed from the ice reserve to the vest. Some of this heat absorption was probably from counter current heat exchange between the fluid flowing from the vest and the fluid flowing to the vest since the flow tubes were adjacent to each other. However, since these fluid flow tubes were exposed to the environment and were not insulated, a significant portion of the temperature rise was probably from the environment. It is likely that by insulating these flow lines a significant improvement to the actual cooling capacity and efficiency of the system can be achieved. Adding insulation to the backpack itself should also reduce heat gain from the environment.

The ice reserve life of the MCS was found to be at least 2.0 hours in the environment tested. It is expected that the life of the MCS will be longer in cooler environments and shorter in warmer environments. The 2.0 or more hours found in this test is encouraging and implies that liquid MCS may achieve the Navy goals of 600 watt-hours of cooling over a two hour period between ice and battery changes if the efficiency, capacity, and reliability of the current system can be improved.

Appendix A. Illustrations

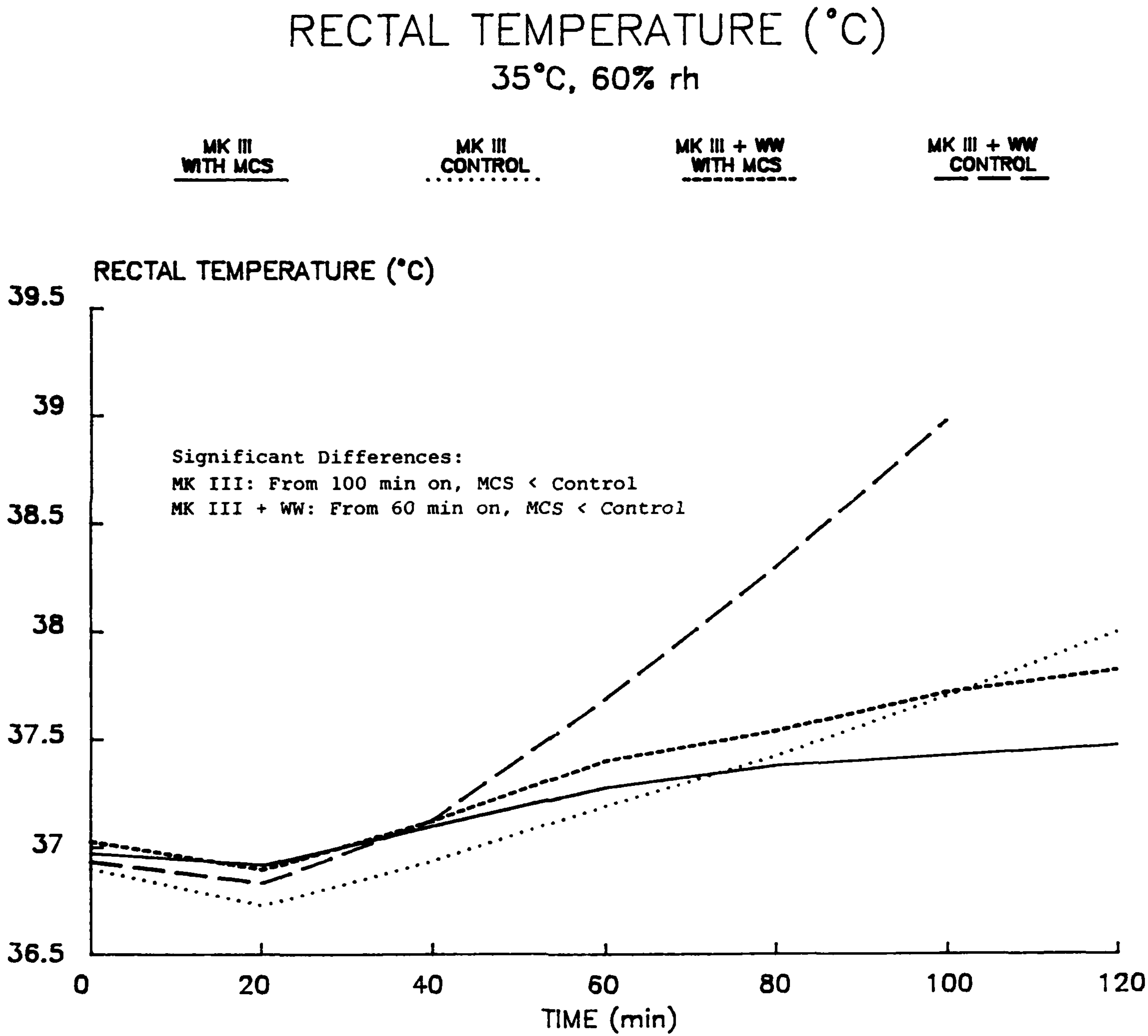

FIG. 1. Rectal temperature responses with and without the cooling system.

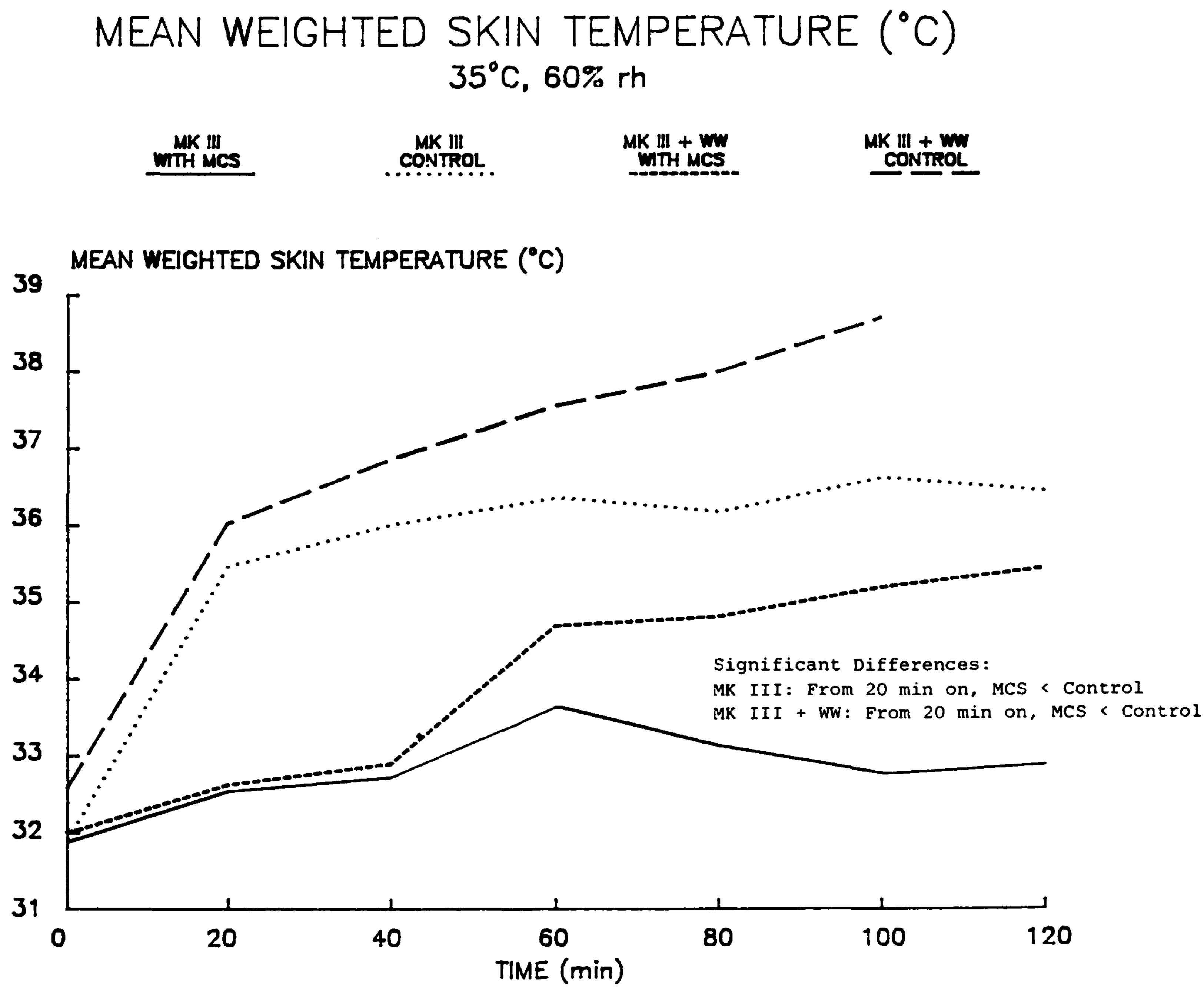

FIG. 2. Mean weighted skin temperatures with and without the cooling system.

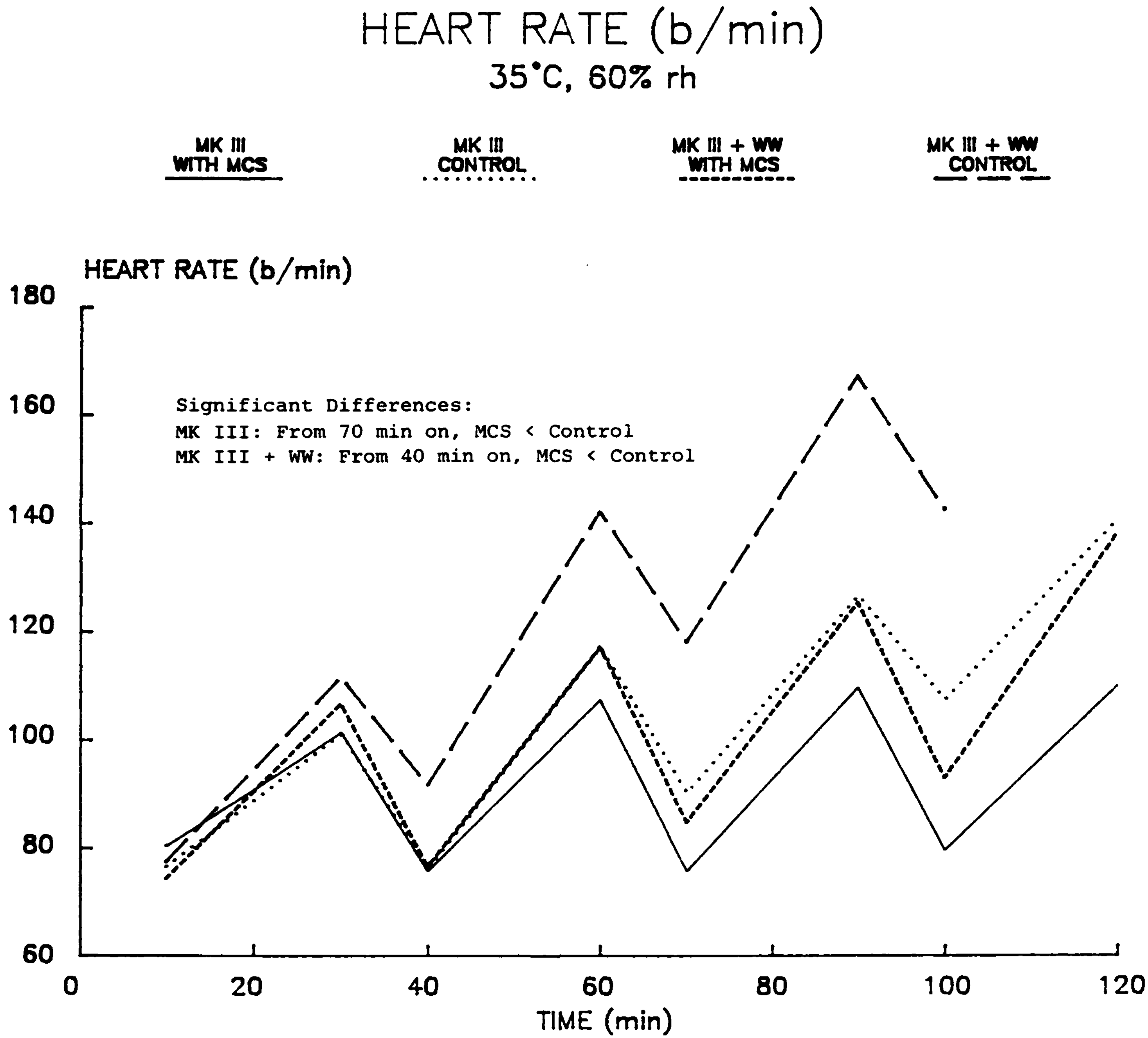

FIG. 3. Heart rate responses with and without the cooling system.

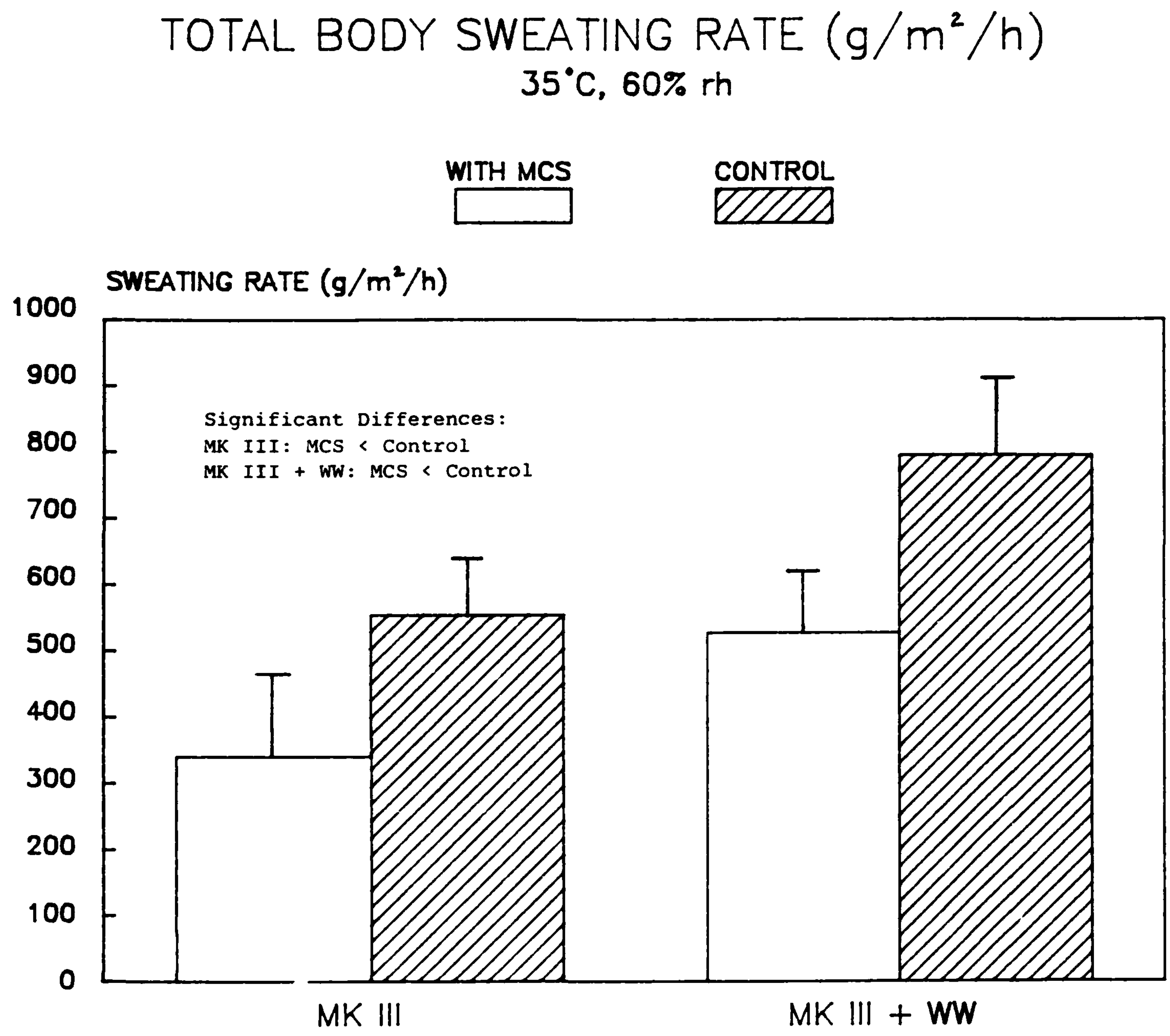

FIG. 4. Total body sweating rates with and without the cooling system; T indicates S.D.

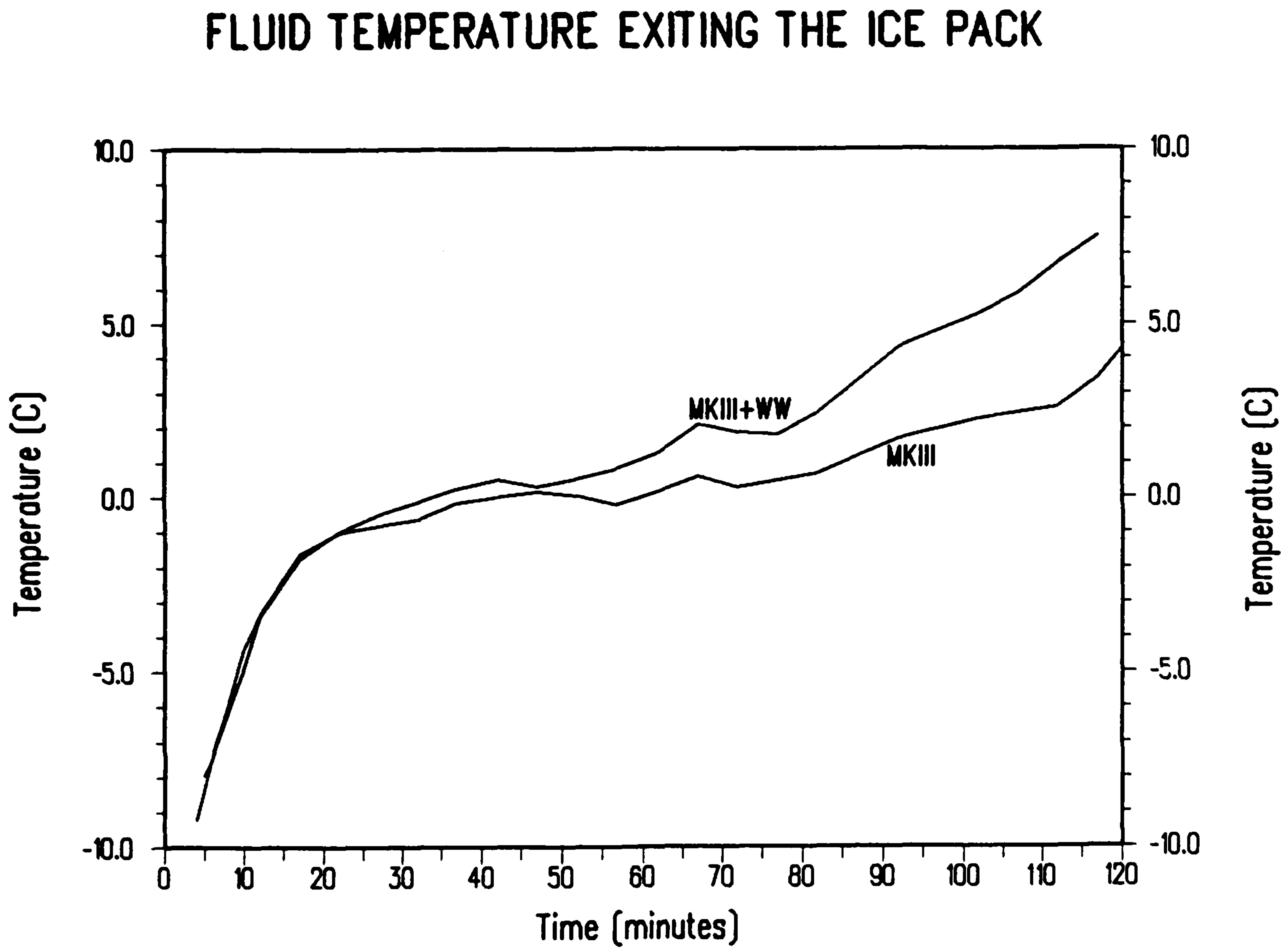

FIG. 5. Time course of circulating fluid temperature exiting the ice pack.

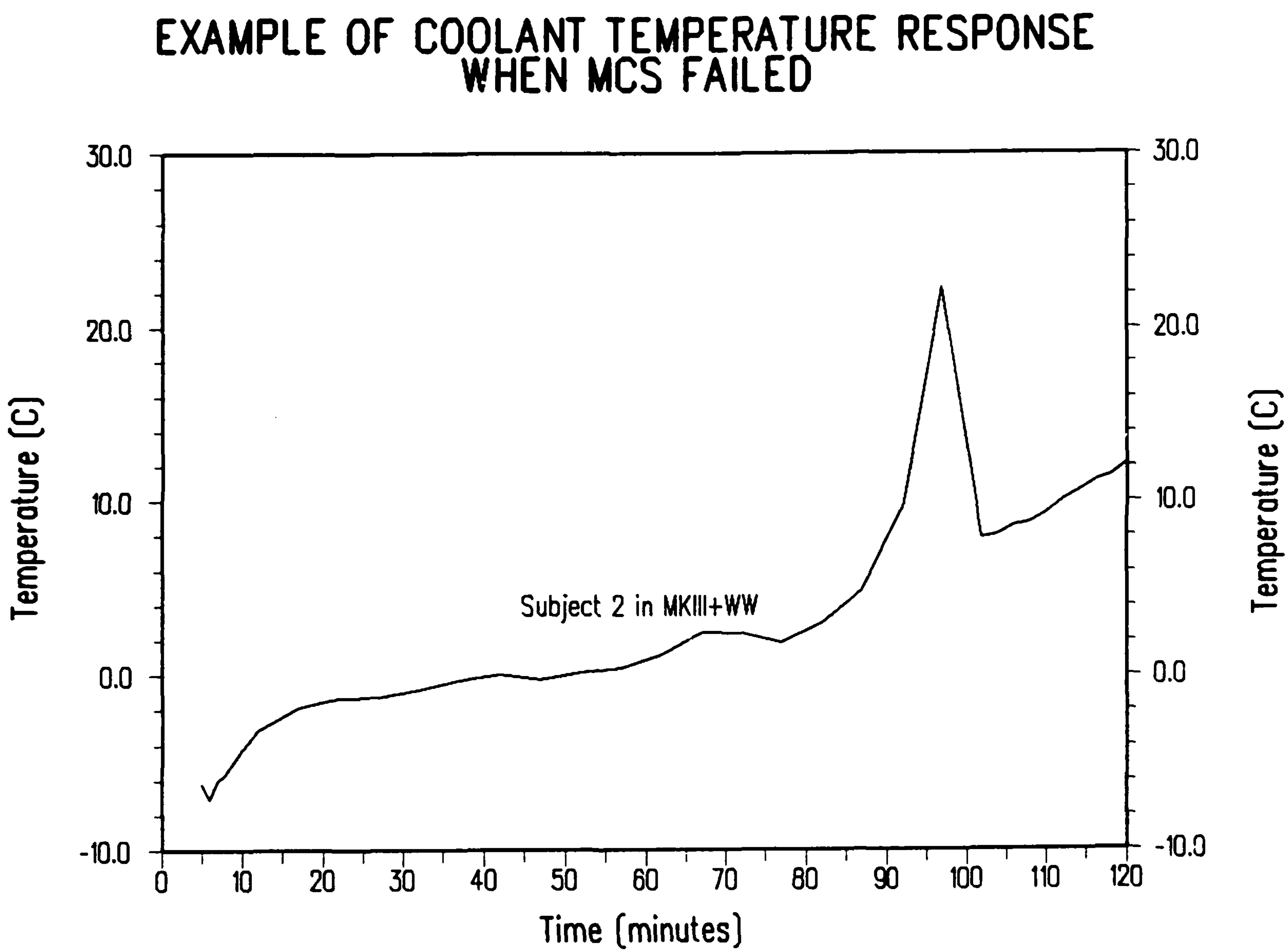

FIG. 6. Example of circulating fluid temperature response when MCS failed during a test.